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August 11, 2009

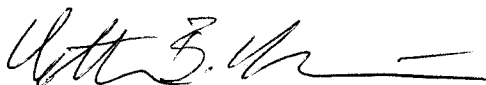
Attn: Paul Baker, Minerals Regulatory Program

Subject: Supplemental Submittal of Appendix C
M/035/002 – Bingham Canyon Mine
Compliance - May 12, 2008 Order Vacating NOV #N2007-58-01
Waste Rock Stability Study and Results of DAN-W

Pursuant to our above noted submittal dated July 30, 2009, please find attached the required Appendix C entitled *FILE05AppendixC-KUCC Waste Rock*. This Appendix was not previous submitted pending updating by the third-party author. Add Appendix C as appropriate into the document submitted July 30, 2009.

Please contact me or Zeb Kenyon at 801-569-6035, should you have any questions concerning this submittal.

Respectfully;



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RECEIVED

AUG 11 2009

DIV OF OIL, GAS & MINING

TECHNICAL MEMORANDUM

DATE: 10 January 2006 (Updated: 06 August 2009)

TO: Glenn Eurick (KUC)

FROM: Mark J. Logsdon (Geochemica)

SUBJECT: LONG-TERM STABILITY OF SOUTHERN WASTE-ROCK STOCKPILES: PHASE I GEOCHEMISTRY

cc: C Kaiser (KUC); Z. Kenyon (KUC); J. Pilz (Rio Tinto T&I); Z. Zavodni (Rio Tinto T&I)

BACKGROUND

Kennecott Utah Copper Corporation (KUCC) wishes at this time to evaluate the Bingham Canyon waste-rock stockpiles with respect to two major issues:

- What infiltration through the stockpiles to their base is expected?
- What geochemical processes are occurring in the stockpiles that could affect slope stability, and are the rates and extents of these processes sufficient to significantly affect slope stability over reasonably foreseeable periods of time?

In 2001, a geotechnical engineer working on rock-pile issues in New Mexico hypothesized that chemical and physical weathering reactions, particularly accelerated attack by acid-rock drainage (ARD), could adversely affect long-term rock-pile stability. The mechanisms conjectured include:

- Diminution of particle size (by either physical or chemical processes), leading to a loss of internal friction
- Conversion of rock-forming minerals, especially feldspars, to clay minerals, producing zones of low shear strength and potentially high pore-water pressure.

Purpose and Objectives

The purpose of this memorandum is to address the status of the geochemical investigations and evaluations of conditions in the Southern rock piles (focused on detail investigations in the Castro dump) at the level of the Phase I investigations. The hydrogeologic and geotechnical conditions are addressed by others.

Specific objectives of the memorandum include:

KUCC: Waste Rock – Long-Term Stability of Castro and the Southern Rock Piles

- Describing the new geochemical investigations on the Castro stockpiles and their results to date;
- Reviewing the relevant geochemical information from other Kennecott technical studies and other relevant studies of waste-rock stockpiles;
- Synthesizing the historic and recent data to the extent practicable;
- Interpreting the geochemical results in terms of potential impacts to slope stability;
- Recommending further work that may be necessary to reduce uncertainties with respect to the magnitude and timing of geochemical impacts, for both the stockpiles currently studied and for others that have not yet been evaluated.

ISSUES

- What is the nature and extent of geochemical reactivity within the KUCC stockpiles?
- What is the likelihood that geochemical reactions would adversely affect the slope stability of the KUCC stockpiles?
- If adverse outcomes were possible, what are the time frames over which such adverse outcomes might be expressed?
- Are positive outcomes possible due to geochemical reactions, and, if so, over what time frames?
- What geochemical work remains to be done to better define and constrain the risk of adverse impacts on slope stability due to geochemical reactions across the full spatial range of KUCC waste-rock stockpiles?

TECHNICAL APPROACH

Phase I geochemical activities followed three principal tracks:

1. Collection and preliminary geochemical analyses of samples from a suite of test pits.
2. Compilation and critical review of existing Kennecott and contractor studies addressing geochemical and mineralogical aspects of the dumps.
3. Evaluation of the rates of geochemical reactions and their implications for in-situ weathering in the rock piles.

METHODS AND PROCEDURES

Test Pits and Screening-Level Analyses

In early April 2005, KUCC excavated 8 test pits for the combined infiltration and shallow-geochemical studies. Test Pits 6, 7, and 8 were excavated on the Castro Stockpile, part of the South End Waste Rock Dump complex. The pits were excavated using a KUCC track-

hoe, following standard KUCC construction methods to maintain safety. Vertical faces were limited to 4 feet, separated by benches of 5 feet.

Eight (8) samples for geochemical analysis were taken from the three Castro pits. The samples were collected by a trained professional geologist and logged and photographed in the field. After initial characterization, five of the Castro samples were split into two size fractions ($> 6\text{mm}$ and $< 6\text{mm}$) and tested on both a whole-sample and a size-fraction basis, producing a total of 13 Castro samples for geochemical analysis, plus field measurements of paste pH and Conductivity on the eight original Castro samples.

The as-received samples (and also the size splits) were tested for paste-pH and paste-conductivity, modified Sobek acid-base accounting (ABA), and single-addition Net Acid-Generation (NAG) tests. All analytical methods were those standardized by KEL. Three samples were sent to Leslie Research and Consulting (Tsawwassen, BC) for petrographic and mineralogical evaluation. The petrographic evaluations included optical (binocular examination of clasts and transmitted and reflected light microscopy of thin sections), X-ray diffraction (XRD) analysis, and scanning-electron microscopy with energy-dispersion analysis (SEM-EDS) to confirm mineralogical identifications. The paste measurements assess current acid-base balance within and across pits. The ABA and NAG data address the potential for additional geochemical reactivity within these reaches of the stockpiles. The mineralogical evaluations explain the nature of secondary minerals (e.g., cements) and illuminate the mineralogical basis for the current and future acid-base conditions.

Document Review

KUCC and contractors on the team identified 19 historical KUCC studies that were relevant to the Phase I activities. Five (5) of these, four dealing with mineralogy (including paste-pH characteristics) and one reviewing the physico-chemical basis for heap leaching, were directly relevant to geochemistry. In addition there was relevant information, for example, on particle-size distributions, permeability measurements, and soils/foundation conditions in other reports, also. The internal reports most important for the geochemical evaluations included

- 1971, Freeman [J.D. Stephens and S. Abou-Zied, Rock Characteristics and Mineralogy of UCD Freeman Dump. MMD-RD TR 71-24]
- 1971, Keystone [S. Abou-Zied, Study of Copper Mineralization in Eleven Samples of Waste from UCD Keystone Dump. MMD-RC Interoffice Memo]
- 1971, Midas [Rock Characteristics and Mineralogy of UCD Midas Dump. MMD-RD TR 72-16]
- 1978, Westinghouse drilling program [P.B. Klinger and W.J. Schlitt, Mineralogical Study of Samples Recovered by the Westinghouse Becker Drilling Program on UCD Dumps. MMD-RC RTR 77-15]
- 1973, Theoretical review [L.M. Cathles, An Analysis of the Physics and Chemistry of Waste Dumps. Ledgemont Laboratory TR C-365 I]
- 1994(?), B.P. Ream and W.J. Schlitt, Kennecott's Bingham Canyon Heap Leach Program. Part I: The Test Heap and SX-EW Pilot Plant. [Undated and unlabelled internal report. There is a 1994 inter-office memorandum from B.P. Ream to R.K.

Davey on the SX-EW Pilot study that is the basis for estimating the date of this report.]

A new report on the mineralogy of samples from this investigation has been produced:

- Jambor, J.L., 2005. Mineralogy of Oxidation Products in Bingham Canyon (KUCC) Waste Rocks. Contractor report to Geochimica, Inc. October, 2005. [Electronic copy on file with D. Cline (RT-TS) and Geochimica].

In addition to the KUCC documents, we reviewed other published literature on waste rock geochemistry, particularly that related to (a) porphyry-copper and porphyry-molybdenum systems and (b) experimental and field-scale data on weathering rates. Important work in the published literature included:

- Cathles, L.M., 1994. Attempts to Model Industrial-Scale Leaching of Copper-Bearing Mine Waste, in C.N. Alpers and D.W. Blowes (eds.) Environmental Geochemistry of Sulfide Oxidation, American Chemical Society Symposium Series 550, p. 123-131.
- Ludington, S.D., G.S. Plumlee, J.S. Caine, D. Bove, J.M. Holloway and D.E. Lowe, 2005. Questa baseline and pre-mining ground-water quality investigation. 10. Geologic influences on ground and surface waters in the Red River watershed, New Mexico. U.S. Geological Survey Scientific Investigations Report 04-5245.
- Wels, C, R. Lefebvre and A.M. Robertson, 2003. An Overview of the Prediction and Control of Air Flow in Acid-Generating Waste Rock Dumps, Proceedings, 6th International Conference of Acid Rock Drainage, Cairns (QLD), Australia, p. 630-650.
- White, A.F. and S.L. Brantley, 1995. *Chemical Weathering Rates of Silicate Minerals*. Mineralogical Society of America, Reviews in Mineralogy, vol 31.

We also considered the October 2005 presentations at the Geological Society of America (2005 annual meeting) Theme Session (Number 175, 18 October, 2005) entitled “Mine Rock Piles and Pyritically Altered Areas: Their Slope Stability and Effects on Water Quality” (GSA, 2005). The most relevant geochemical information was presented by Campbell et al (2005), which showed that the jarosite forming in natural weathering of Quartz-Sericite-Pyrite altered volcanic rocks at Questa, NM were 300,000 – 1.8 million years old.

Geochemical Evaluations of Rates and Impacts

Working from literature values, we have made some preliminary calculations of weathering rates (especially rates of generating clay minerals from primary aluminosilicates) and tried to relate them to the observed weathering in KUCC stockpiles. In doing this we follow, in part, screening approaches suggested by Lasaga (1998) and Jambor et al. (2000), and in part a numerical modeling approach suggested by Bethke (1996; 2005) as it might be applied to the KUCC rock piles. The numerical modeling uses both full equilibrium and kinetic models of the geochemical interaction between acidic infiltration and “granitic” rocks.

PHASE I GEOCHEMICAL RESULTS

Field information, acid-base accounting data and mineralogical results are available in the contractor reports (too large to make a credible attachment) on file with Rio Tinto or from Geochimica. The key findings from the geochemical testing for the Castro stockpile to date include:

- In the Castro pile, cap-rock and test pits containing predominantly intrusive rock have low pH and elevated conductivities. However, Test Pit TP06 was excavated into predominantly calc-silicate rock, and below the intrusive cap the pH of this material remains circum-neutral (pH 6.88-7.6), and the conductivity values fall toward the low end (near 2,000 uS/cm) for all samples tested.
- When the samples are split into size fractions, the finer fraction (silt and smaller-size) has lower pH and generally somewhat higher conductivity.
- The bulk-sample paste-pH values measured immediately after excavation tend to be distinctly lower paste-pH and paste-conductivity values than those measured several weeks later. The reasons for these trends are not known at this time. Jambor (2005) reports that no additional minerals precipitate during air drying of samples, so precipitation of soluble salts during evaporation does not seem a likely cause. Perhaps there has been some precipitation of low-solubility phases that incorporate some of the labile acidity, as for instance hydronium (H_3O^+) ion in jarosites that do not re-dissolve in the paste procedure.
- Although moisture contents below the very-near-surface of the pile were low and the system was entirely unsaturated, in the Keystone dump there is moist, warm to hot air venting upward through coarse layers in the waste rocks. Some vents reach the dump surface on Keystone, where they appear as water-vapor “fumaroles” on cool days. Such temperatures or evidence of warm-air movement was not seen in Castro during the 2005 field work.

The mineralogical evaluation (Jambor, 2005) includes the following key results, focusing on the Castro samples:

- The samples from Castro includes not only quartzite and intrusive, but also a significant fraction of carbonate-bearing calc-silicate.
- The only secondary minerals that appear as coatings and cements are jarosite [$(\text{K}, \text{H}_3\text{O}^+)\text{Fe}^{\text{III}}(\text{SO}_4)_2(\text{OH})_6$]¹ and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Although very tiny amounts can be identified in SEM-EDS investigations, the effective absence of goethite (FeOOH) or its predecessor, ferrihydrite ($\text{Fe}(\text{OH})_3$) is noticeable. There is no significant difference between the jarosites in the leached sample from Code 51 and the jarosite in the unleached samples from Keystone and Castro.
- Limestone remains inside partially skarnified clasts in the Castro sample. This is consistent with the measured Neutralization Potentials. In Castro samples containing the calc-silicate clasts, the paste-pH values are all close to pH 7.

¹ True jarosite contains K; the hydronium-substitution is well known mineralogically, but requires a low-potassium and high acidity system and is rare in most mine-waste systems. The significance of hydronium jarosite is discussed below.

- There are no identifiable examples of either newly-formed clay minerals or secondary, amorphous silica, even in the samples with circum-neutral paste pH and observable limestone in the calc-silicate matrix. There are rare clay minerals in some of the intrusive fragments, but these appear to be hypogene hydrothermal minerals that do not reflect clay generation in the pile after mining. The only silicate mineral that shows alteration is biotite (a hypogene phase), which is transformed to an interlayered mineral, called “hydrobiotite”, that has alternating layers of biotite and K-free vermiculite. The incongruent leaching of K from biotite is the source of the K^+ ions that now reside in the jarosite. Where biotite is absent in clasts, the jarosite is either a mixed $K^+ - H_3O^+$ or a true hydronium jarosite.

The mineralogical results for the 2005 samples are consistent with the observations of jarosite dominance and lack of evidence of newly-formed clays in the 1970's studies by Kennecott.

RESULTS OF THE LITERATURE REVIEW

During the 1970s (particularly), Kennecott staff extensively reviewed the geochemistry and hydrology of the rock piles in order to understand how to optimize leaching. The leaching process was based on reacting strong acids with the rock piles at rates that greatly exceed similar reactions occurring as a result of natural ARD (Acid Rock Drainage). The increased rate of reaction (compared to meteoric conditions) arises from two factors:

- The lower pH and much higher total acidity of the leach solutions compared to meteoric solutions;
- The much higher, and more consistent, application rate of leach solution compared to natural infiltration through the piles.

Key results from geochemical and mineralogical evaluations (especially of the Freeman, Midas and Keystone piles – those investigations did not significantly address the limestone-bearing southern rock piles because they were not suitable for leaching because of their high carbonate content) in the 1970s include:

- Paste-pH values ranged from about 2 to about 4, with average values near 3.5, and paste-conductivity values were in the range of several thousand uS/cm. These values are indistinguishable from values obtained in 2005 outside the calc-silicate zone of Castro.
- There were zones within the rock piles with ambient temperatures up to 130 F (50 C), and oxygen contents approached atmospheric levels (15%-20% of total air volume) throughout much of the pile and were detectible (at up to 3%) everywhere tested. These results imply a well-oxygenated pile in which sulfides (especially pyrite) are actively oxidizing to produce the observed heat.
- The principal secondary minerals were jarosite and gypsum, again identical with the 2005 results. [One of the early mineralogical reports discusses clay minerals (especially kaolinite) and amorphous silica in “clay-rich” matrix surrounding some lithic clasts, but the X-ray diffraction, optical, and microbeam reports do not identify these as newly formed, and the text makes a point of stating that the mineralogy of

the rocks at the time they were deposited is not known, so the clay minerals cannot be shown to be newly formed.]

- Carbonate minerals were entirely absent from all leached rocks. This also is the observation in the new 2005 work., however limestone was clearly present in some Castro samples in the Southern Rock Pile complex

There are some important results in the older work also in terms of hydrogeology and geotechnical parameters. The significance of these for infiltration will be addressed primarily by others, so this discussion will focus on results potentially important for geochemistry.

- There is a bimodal distribution of particle sizes in the 1970s studies, with a large portion of the tested samples having lower hydraulic conductivities [$K < 10^{-3}$ cm/s; ($k < 1$ darcy)], whereas other portions represented gravel or larger-sized coarse zones with very high hydraulic conductivities [$K > 1$ cm/s; ($k > 1000$ darcy)]. In all three leach dumps, 10% - 20% of the particles pass the 200 mesh (and are called “slimes” in the early reports, based on an operating term appropriate to tailing). Hydraulic conductivities in these materials probably would be about 10^{-5} cm/s to 10^{-6} cm/s ($k = 1$ millidarcy) or less. It seems likely, based on both the site-specific mineralogical analyses and observations in other mine sites, that the fines represent hypogene mineral phases, which may have, in part, migrated through the coarser layers to accumulate with other, finer material (silty-sand sized layers) during settling and infiltration.
- In 1982, KUCC conducted a particle-size distribution study for run-of-mine rock. This study found that only a few percent (certainly $< 5\%$) of the tested samples passed the 200 mesh. Although it is not entirely clear that the run-of-mine rock that reported to the Southern dumps prior had the same particle-size distribution as the samples tested in 1982, there is no reason based on the lithologies to expect much higher fines content, and the available data indicates that the clay-sized fraction is sufficiently small that it would be unlikely to influence the bulk mechanical behavior of the rock pile..

The bimodal permeability structure is the macroscopic fluid-phase expression of the alternating coarse- and fine-layering seen in the piles when they are excavated. This permeability contrast controls the flow of air and heat primarily through coarse layers and fluids migration predominantly in the fine layers as a consequence of the basic physics of fluid flow in porous media under unsaturated conditions.

DISCUSSION

Geochemical Reactivity

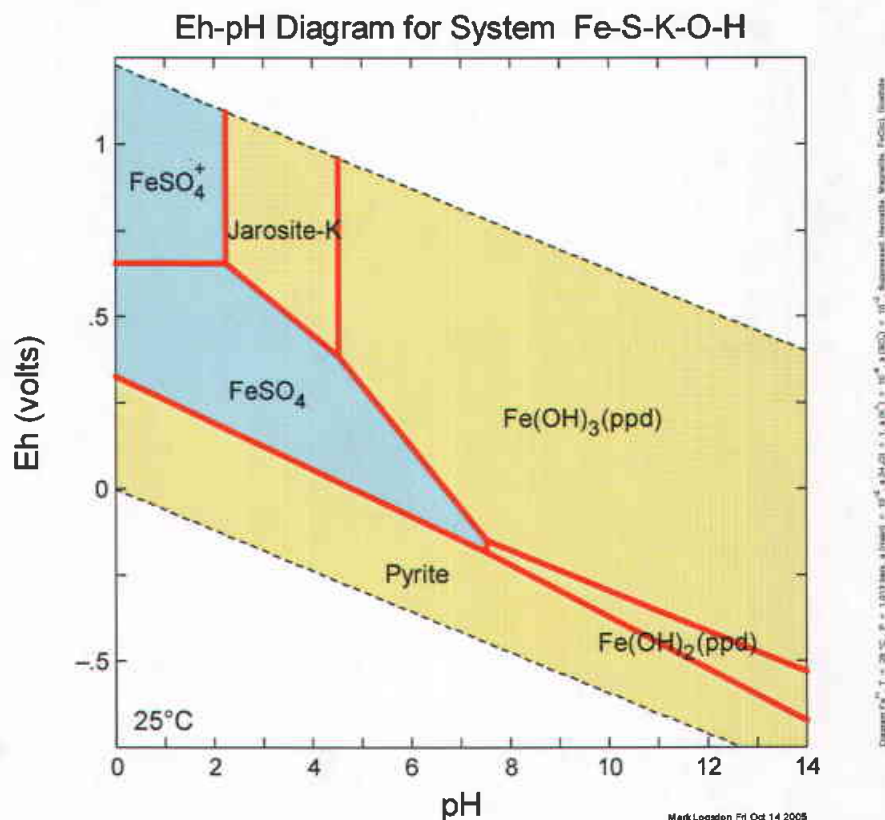
There is a body of geochemical data, especially in seepage water-quality, that shows that the rock piles, both those that have been leached and those that have not, are geochemically active. The 2005 observation of residual pyrite in waste-rock samples that have no residual neutralization potential (outside the Southern rock piles) implies that the observed pyrite oxidation that leads to the low-pH conditions will persist well into the future.

The observation, consistent from 1971 to present, that the majority of the secondary minerals produced by reactions in the Kennecott rock piles is jarosite and gypsum, and the absence of carbonates in non-calc-silicate rocks, implies that the principal reactions are:

- Oxidation of pyrite (FeS_2) to release Fe and S that oxidize to Fe^{3+} and SO_4^{2-} . Pyrite oxidation is acid-generating. In addition, the recycled leach solutions contained abundant additional Fe^{3+} , added to the solutions in the Precipitation-Plant reactions. An important matter is understanding the point made by Cathles (1973) that the principal oxidant of sulfides in the piles is Fe^{3+} ion, and that the principal role of the high oxygen levels within the pile is to ensure that the dissolved iron will be maintained overwhelmingly in the Fe^{3+} (ferric) state.
- Incongruent dissolution of biotite to hydrobiotite releases K^+ to pore waters. The oxidation reactions are sufficient to form pH conditions low enough to stabilize jarosite $[(\text{K}, \text{H}_3\text{O})\text{Fe}(\text{SO}_4)_2(\text{OH})_6]$ instead of ferrihydrite $[\text{Fe}(\text{OH})_3]$ (see Figure 2). Where there is sufficient K^+ locally available, the jarosite is a classical K-jarosite. Where K is deficient, the pH is sufficiently low to allow abundant H^+ ions to react with water to produce the hydronium (H_3O^+) seen in the hydronium jarosites documented in Jambor (2005). A significant feature of the geochemistry of all Kennecott dumps examined to date is that jarosite, not ferrihydrite, dominates the iron precipitates that form cements and coat clasts.
- Dissolution of calcite (CaCO_3) by the acidity generated from sulfide oxidation to eliminate the original carbonate minerals and provide the Ca^{2+} that is now present in newly formed gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).
- Although one early report (the 1971 Freeman report) qualitatively described kaolinite and amorphous silica in the leach dumps, this was not confirmed in the mineralogical reports, and the 2005 sampling did not identify any clay minerals that were formed in place. The 1971 report concluded that the kaolinite and other clay minerals in the pile probably were largely if not entirely hypogene and unrelated to any geochemical reactions within the pile after mining.

Figure 1 outlines the major stability fields of secondary minerals and fluid compositions in terms of pH and oxidation state, in the familiar Eh-pH diagram (e.g., Bethke, 1996).

Figure 1 Eh-pH Diagram for Relative Stability Fields of Jarosite, Ferrihydrite, and Pyrite (Figure calculated in Geochemist's Workbench, Rel 6.0, Bethke, 2005)



Jarosite is stable under highly oxidizing conditions and pH values between about 2 and 4.5. Ferrihydrite ($\text{Fe}(\text{OH})_3$) is stable at higher pH. Goethite (FeOOH), is an aged, dehydrated iron hydroxide phase that would form over long time periods, ultimately encompassing the field of both ferrihydrite and jarosite (Jambor et al., 2000). Calcite, the major mineral in limestone, is unstable at pH below 6, so a system precipitating jarosite must be dissolving calcite. The iron disulfide, pyrite, is stable only under reduced conditions. In the waste-rock pile, which is well oxygenated, pyrite oxidizes, with the iron ultimately reporting to a secondary hydroxysulfate (jarosite) or hydroxide (initially ferrihydrite).

Reaction Rates and Implications for Dump Stability

Excluding small-scale unraveling and shallow slips near dump toes, dump-stability issues at Bingham Canyon have been associated with fluid management in the leach systems (Pennicheckle, A.D. and M.B. Kahle, 1971. *Stability of Waste Dumps at Kennecott's Bingham Canyon Mine*. Transactions of AIME, vol. 250, p. 363-367). The dumps have histories extending back prior to 1930, so there is at least a 75-year history that shows that the conjecture of geochemical instability is not significant to time periods on the order of 100 years, so long as fluids are well managed (or the piles are not leached, for example the Castro

rock pile). It is worth looking into the fundamental controls that may explain this and trying to estimate some rates for important reactions that may help estimate the long-term stabilities.

One may analyze the basic conditions for slope stability in terms of shear strength:

$$\tau = c + (\sigma_n - p_u) \tan \phi$$

where τ = shear strength
c = total cohesion,
 σ_n = normal stress
 p_u = water pressure
 ϕ = friction angle

[W. Wilson, personal communication, 2005]. The cohesion term (which could, in principle, be measured in intact samples at ambient moisture content) can be divided into a “true” cohesion term encompassing adhesion, cementation and the effects of stress history, and an “apparent” cohesion due to matric suction in unsaturated materials.] The two critical geomechanical parameters, then, are friction angle and cohesion. It should be noted that conventional slope stability analyses generally ignore cohesion entirely and conservatively assess stability in terms of friction angle alone. However, a notable feature of several of the KUCC leach dump is that they have cemented into ferricretes² that are so strong, that, at least in some cases, they must be blasted to move the pile (Pennichele and Kahle, 1971; Z. Zavodni, personal communication, 2005; V. Peacey, personal communication, 2005.). In other dumps, the cements exist only as a thin crust on dump surfaces (J. Pilz, personal communication, September 2005), and some dumps can be excavated without blasting (B. Vinton, personal communication, 2005).

Friction Angle and Geochemistry

Friction angle will be a function of particle size, particle interlocking (density) and shape. Processes that would tend to reduce particle size (e.g., conversion of feldspars to clay minerals) or that would tend to smooth rough surfaces would tend to reduce friction angle, and therefore move a pile that originally was stable due to friction alone toward a state of instability. This is the essence of the geochemical-instability conjecture.

The question then arises: at what rates would one expect rock-forming minerals to dissolve? This has been a very active area of geochemical research in the past 10 – 15 years. A useful summary is presented in Lasaga and Berner (Lasaga, A.C. and R.A. Berner, 1998. Fundamental aspects of quantitative models for geochemical cycles. *Chemical Geology*, vol. 145, p. 161-175.) and reproduced here as Table 1.

² “Ferricrete” refers to a material, visually similar to concrete, in which clasts (the “aggregate”) is cemented by an iron-rich matrix. In the general case, that matrix can be ferrihydrite ($\text{Fe}(\text{OH})_3$), goethite (FeOOH), or jarosite ($\text{KFe}(\text{SO}_4)_2(\text{OH})_6$). In the Bingham Creek piles, the cement is primarily jarosite.

Table 1 Mean lifetime of a 1 mm crystal at 25C and pH 5 (minerals directly relevant to Bingham waste rock highlighted)

Mineral	Lifetime (year)	Mineral	Lifetime (year)
Calcite	0.43	Albite	575,000
Wollastonite	79	Microcline	921,000
Forsterite	2300	Epidote	923,000
Diopside	6800	Muscovite	2,600,000
Enstatite	10,100	Kaolinite	6,000,000
Sanidine	291,000	Quartz	34,000,000

The minerals considered by Lasaga and Berner were pure minerals. If, in a mineral deposit such as Bingham Canyon, some of the minerals had been affected by hydrothermal conditions prior to mining, it could be that their dissolution behavior would be different from that considered by Lasaga and Berner. Additionally, reaction rates would be slightly higher at 50 C and at pH 3.5 than those considered in the original study. It should be noted, however, that in Jambor's detailed evaluation of current samples (Jambor 2005), he found no evidence for alteration of any hypogene phase except biotite. In any event, the relative rates would remain the same, and even if the rates were 10 times higher, the basic information remains the same. The most important features of this table are:

- The only fast-reacting (less than several decades), rock-forming mineral is calcite. This is expected to be the case also at Bingham, based on the mineralogy of country rocks and intrusives.
- Skarn minerals known at Bingham include wollastonite and diopside, and the reaction rates for these are long compared to calcite. Therefore clasts of calc-silicate rock may contain residual limestone that is protected against acid attack by the rind of skarn minerals (see Jambor 2005 for an example from Castro dump).
- The principal rock-forming minerals of the intrusive rocks and quartzite would not be expected to dissolve in any time period of interest to this evaluation.

In summary, except in limestone-rich rocks that may come in contact with ARD, large-scale dissolution, sufficient to reduce friction angles significantly in the rock-forming minerals at Bingham would require tens to hundreds of thousands of years. Where carbonates are present, as in the calc-silicate rocks at Castro in the Southern complex, the natural acidity (these were not leached) would be neutralized and all reactions would be very slow. Certainly, coarse-rock zones in the piles would be almost entirely unaffected, unless the clasts were limestone that is not rimmed with skarn. Supporting this long time frame, radiometric dating of weathering minerals (jarosites) in naturally weathered Quartz-Sericite-Pyrite altered igneous rocks at Questa, NM show that the alteration process there has taken 300,000 to 1,8 million years to produce the natural "scars" seen on the sides of the valley there (Campbell et al., 2005).

Cohesion and Geochemistry

The most extreme cohesion seen in rockpiles arises from the precipitation of secondary cements in open pore space. This is very evident in the calc-silicate zones of the Castro rock

pile, where jarosite has completely filled the open pore space, producing a “ferricrete”: a ferric-iron cemented material that resemble concrete, in which the “aggregate” is the pre-existing rock fragments of what was a porous medium. The effect is striking in Figure 2 (from Jambor, 2005).

Figure 2 Cementation (as ferricrete) of limestone clasts by jarosite (reddish-brown) in Castro Dump [‘puck’ diameter ~32 mm]



A ferricrete such as illustrated in the two clasts on the left side of Figure 2, must be sawed with a diamond blade or broken by percussion with a heavy hammer

The sort of cementation seen in Figure 2 is not limited to Castro. Other parts of the leach dumps, which were under leach for decades, have yet more extensive cementation, as shown in Figure 3. As discussed above, in some places in the leach dumps, the cementation is sufficiently robust that, if the dumps need to be deconstructed, drilling-and-blasting is required, as has been observed recently on historic dumps rimming the east, west and northwest walls of the Bingham pit, and some faces of up to 50 feet remain vertical after excavation (V. Peacey, personal communication, 2005).

Figure 3 Major zone of ferricrete cementation in West-Side leach dump (Photo is courtesy of Z. Zavodni, RT-T&I, 2005)



The leach solutions used by KUCC were a very advanced form of “acid-rock drainage”: low-pH, high-iron; high sulfate solutions derived, ultimately from pyrite oxidation in the rock piles themselves. The mineralogy, based on X-ray diffraction and scanning electron microscopy as well as by standard methods of optical petrography, of the cements examined in 2005 (and as described in the 1970s) is essentially identical whether the rocks have or have not been leached. Therefore, it is geochemically reasonable to infer that the process of cementation seen in the leach dumps also would occur in the non-leached dumps, although the extent of iron precipitation in the leach dumps is related to the very high concentrations and large total mass fluxes of iron in those systems during the leaching history. There are some bounding calculations that one can use to assess the differences between the leached and unleached dumps and to assess whether, and when, an unleached dump can achieve the degree of cementation seen in the leach dumps.

The amount of jarosite present as a cement in a dump is a function of the amount of iron and sulfate that has flowed through that pore space, because there is 1 mole of Fe and 2 moles of SO_4 for every mole of jarosite $[\text{KFe}(\text{SO}_4)_2(\text{OH})_6]$ present. Now, the flux of Fe^{3+} and SO_4^{2-} through the forced-leach dumps is several orders of magnitude (probably >3 orders of magnitude) greater than in non-leached dumps. This arises from the high water application rates and the high concentrations typical of the recycled leach solutions. Cathles (1973) states that the application rate of leach solution on the full-scale Midas dump was about 0.25 gal/ft²/hr³, or $8.92\text{E}+1$ m/yr (per m²), which is about 2 orders of magnitude higher than the average annual precipitation (estimated at 700 mm). In fact, because the dump application was maintained as ponded water for long periods, the infiltration was probably another order of magnitude higher than that under natural conditions (estimated at about 15% and certainly less than 30% of annual precipitation by M. O’Kane, personal communication, 2005). In addition, total iron concentrations in acidic drainage from porphyry-style rocks is usually around 100 mg/L (e.g., Plumlee, 1999), whereas the recycled leach solution would have been close to 10 g/L, and certainly above 1 g/L, so there would be another 1-2 orders of magnitude increase in flux associated with concentration alone. Thus, the flux of Fe^{3+} in the system while the rocks were under leach was probably 3 to 7 orders of magnitude higher than would be expected in the unleached rock piles, and this is the principal reason why there are extensive zones of dense, jarosite-rich ferricrete in the leach dumps, whereas cementation in the unleached zones that we observed in 2005 in Keystone and Castro were limited and somewhat ephemeral (except in the calc-silicate zones as shown in Figure 2).

In his 1973 paper, Cathles calculates a “characteristic time” for complete leaching of the Bingham dumps. The “characteristic time” is a concept derived from chemical engineering, where it represents the period required for full reaction in a given volume undergoing flow at a given average rate. Cathles’ calculations, supported by laboratory and field-scale data, showed that the characteristic time for UCD dumps under leach was about 380 months, or 30 years. Given that the flux rate of Fe^{3+} was very much greater than that expected for the non-leach dumps operating under meteoric flow, suggests that for natural meteoric

³ Cathles (1973) states that the application on the Midas test Pad was 0.26 gal/ft²/hr and that the application rate to the full-scale pile was 10 times higher.

conditions to approach those seen in a fully-leached dump (e.g., Figure 3) would require very long times.

Despite the likelihood that meteoric dumps would not achieve the degree of cementation seen in the leach dumps for very long times, the basic geochemical behavior is such that the dominant outcome is clearly a trend toward increased cohesion. The geochemical reactions that tend to increase cohesion by producing cements occur very much faster (weeks to months, as seen in the leach dumps during operations), compared to thousands or tens of thousands of years needed for dissolution to adversely affect internal friction characteristics of even fine-grained portions of the system.

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions of the Phase I study with respect to the Southern Rock Piles include:

- Rock piles are geochemically active and producing acidic drainage or locally (where limestone is present) neutralized but high TDS seepage that precipitates gypsum.
- Pyrite oxidation reactions will persist far into the future, probably hundreds of years or more, based on the amount of pyrite remaining and the oxidation rate of pyrite in air.
- There is no evidence from the new or old mineralogy reports that feldspars and other alumino-silicates are being converted to clay minerals at rates that lead to observable amounts of clay minerals in periods of several decades.
- There is active precipitation of secondary, cementing minerals, largely jarosite $[\text{KFe}(\text{SO}_4)_2(\text{OH})_6]$ and lesser amounts of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), in both leached (Code 51) and non-leached (Keystone and Castro) dumps.
- The mineralogy of the cements does not depend on the lithologies of the local clasts.
- The amount of cementation is greater in the leach dumps than in the non-leach dumps, because a very much greater flux of Fe^{3+} and SO_4^{2-} have passed through the leached dumps.
- There is no reason to expect that the ferric minerals precipitated in the waste-rock dumps would become chemically unstable and dissolve. They may convert over time to a more goethite-like ferric hydroxide (FeOOH), but this is expected to occur over centuries or even longer and would leave the dumps still iron-cemented. Gypsum in very shallow zones may be subject to dissolution and re-precipitation cycles, during shallow infiltration events, but this is unlikely to be important more than a very few meters below ground surface.
- Because the geochemical processes and the initial rocks are identical mineralogically, the non-leach dumps will evolve toward conditions such as those seen in the leach dumps, i.e., increasing cementation (cohesion) over time.
- Dissolution of particles as a mechanism for grain-size reduction cannot occur at a rate sufficient to significantly reduce internal friction in the dumps over time periods on the order of hundreds to a few thousands of years, and probably would require tens to hundreds of thousands, or even millions of years.

- Therefore, we conclude that the geochemical trends in waste rock dumps, specifically including Castro and the other Southern Rock Piles, are toward greater stability, through addition of true cohesion, rather than toward instability due to particle-size reduction and loss of internal friction.

We recommend that the Phase I team and KUCC personnel meet to discuss the outcomes, conclusions, and limitations of the interim study and determine whether additional studies are warranted at this time. A further search for relevant in-house files is justified. Expansion of the program to other dumps on a near-surface basis could be accomplished with a scope very similar to that used in Phase I.

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Additional citations, especially internal Kennecott documents, that were consulted, are cited in full in the text.